Responses of fractal dimensions of *Picea koraiensis* seedlings to different light environments

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Abstract: The changes of fractal dimension of *Picea koraiensis* seedlings under different light intensities in natural secondary forests was studied. The results showed that with the change of light environment, crown characters of *Picea koraiensis* seedlings exhibited a greater plastic in lateral number, lateral increment, lateral dry weight, and specific leaf area. The range of calculated fractal dimensions of seedling crowns was confined between 2.5728 and 2.1036, but maximum of fractal dimension achieved in term moderate shading and in extreme low light conditions fractal dimension was least.

Key words: *Picea koraiensis* seedling; Fractal dimension; Different light environment.

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Introduction

Natural lines, such as coastlines, mountain outlines, or boundaries between forest types, usually have spatial dimensions, called "fractal dimensions," that are greater than one. The excess over one indicates the amount of convolution within a line. Similarly, the dimensions of natural surfaces exceed two. Natural lines are hybrids between ideal lines and surfaces, just as classical surfaces and volumes serve as the ideal extremes of actual surfaces.

Tree crown is a truly fractal object, a mass fractal. It is difficult to describe its shape in terms of Euclidean geometry. The best we can do is to measure lengths, diameters, and angles of many branches, twigs and leaves. The problem of extracting a few meaningful numbers that will characterize the crown as a whole remains unsolved within the framework of classical methods. Whatever its intrinsic merit, fractal geometry does not immediately solve all forestry problems. The two-surface method is the first and so far the only workable method for determining the fractal dimension of real tree crowns as opposed to their two-dimensional projections. Zeide (1991) showed that fractal dimension of crowns, in addition to its direct application to quantifying surfaces and areas, can serve as an indicator of species, tolerance, crown class, and foliage distribution within a crown. To improve our understanding of shade tolerance, we studied responses of fractal dimensions to different light environments of planted seedlings of *Picea koraiensis* in natural secondary forests in Changbai Mountain.

Materials and methods

Study sites and seedlings

Study sites were located near the Opened Research Station of Changbai Mountain Forest Ecosystems (42°24' N, 128°28' E). The mean annual precipitation was 760 mm, and mean annual temperature is 4.9-7.3 °C. There are two months with mean temperature > 10℃. Soil type is the mountain dark brown forest soil.

The growth of *Picea koraiensis* seedlings were exposed to a variety of light environments from an open light to different density in natural secondary forests. The above-canopy density was from 0 to 0.3, 0.5, and 0.8, and each canopy density was ordinal called "E0, E1, E2 and E3". On each site, approximately 150 seedlings with no apparent competition for light from shrubs and herbs, and no apparent damage, were sampled systematically along each line.

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Measurement of crown surfaces and volume

To obtain volume of seedlings crown, we summed three sections of seedling crown. Top section is considered as either cone, and lower section is treated as frusta of right cones. We computed the volumes of the sections from measurements of their length and width. Although not all-horizontal cross sections of a crown are circular, the large number of measurements assures the unbiased estimation of the convex hull volume. Volumes of needle-free cavities, approximated as paraboloids, were subtracted from the sum of the sections' volume.

The samples for surfaces of conifer leaves were systematically taken from approximately 25~30 saplings along transect lines with an attention of distributed light conditions at each study site. The leaf area measurements on laterals were taken. To eliminate the variation of lateral branch increment from individual lateral branch, each sampling was length of all measured laterals. Leaves on each laterals were removed from 4-cm branches for measuring the surface area, projected leaf area (cm^2) was measured with a LI-3000 leaf surface area meter.

Estimating self-similarity of seedlings crowns

The two-surface method assumes the relationship between the foliage area and Euclidean surface (A), and the area of the convex hull (E) is described by a power function (Equations (1) and (2)).

$$A=aE^{D/2} \tag{1}$$

where a is a constant. Thus, fractal dimension is defined as a parameter of the relationship between the two surfaces of a crown.

$$A=bV^{D/3} \tag{2}$$

where b is a constant, V is volume of the convex hull. The equation (2), too, allows one to estimate the fractal dimension. For this reason, this relationship is indeed linear (3) and not curved (Zeide 1991).

$$\mathrm{Ln}(F) = a + (D/3)\,\mathrm{Ln}(F) \tag{3}$$

To test the observed departure from linearity, the squared term of the independent variable was introduced:

$$\mathrm{Ln}(F) = a + b\,\mathrm{Ln}(V) + c\,\mathrm{Ln}(V) \tag{4}$$

Calculation fractal dimension

If the relationship is a power function the fractal dimension can be calculated by equation (3), where D is fractal dimension.

Results and discussion

Crown architecture of seedlings under variety of light environments

The height and lateral growth performance was used to describe crown architecture. In E1 light environment, *Picea koraiensis* seedlings had a greater increment in height and total lateral number and specific leaf area (SLA) than in open light. With decreasing light under canopy of crown, *Picea koraiensis* seedlings had decreased in lateral number and height growth performance. Although total lateral number in E1 light environment is greater than in open-light, lateral dry weight had a significantly lower mass than in open-light (Table 1).

Each species has genetically inherent biomass allocation pattern (Tilman 1988). A species allocating more biomass to branch growth has greater ability to capture light in light-limiting environments (Oliver and Larson 1990). Some genetically inherent characters of a species may be plastic within a certain range in response to environmental changes (Ducrey 1992). In general, growth measures do not necessarily explain the total carbon gain that reflects the relative capacity of *Picea koraiensis* seedlings to utilize limiting light resources by height, lateral lengths and leaves measurements.

Table 1. General characteristics of seedlings grown under variety of light environments

Character	Light environments							
	E0		E1		E2		E3	
	Means	SD	Means	SD	Means	SD	Means	SD
Height (cm)	35.39	8.21	36.18	5.35	33.87	6.81	34.97	8.21
Mean lateral increment (cm)	6.03	1.80	5.71	1.23	5.26	1.02	4.48	1.80
Total lateral number	17.10	4.22	22.84	5.95	21.37	4.93	15.52	8.22
Lateral dry weight (g)	5.97	0.94	3.89	1.39	3.56	0.67	2.97	0.88
Leaf dry weight (g)	5.97	1.24	3.90	0.65	3.58	1.32	2.98	1.29
Specific leaf area ($cm^2 \cdot g^{-1}$)	3.95	0.58	4.35	1.02	2.89	0.90	2.43	0.25

SD is standard deviations ($P<0.05$).

To determine surface architecture of foliage with the differences in light conditions, allometric analysis was used to examine morphological responses to wide range of light environments. Because foliage

mass is proportional to foliage area, relationship between the leaf weight (L_W) and above-ground biomass (A_B) can be appropriate to estimate the responses of surface of the convex hull (Table 2).

Table 2. Relationship between the leaf weight (L_W) and above-ground biomass (A_B)

Light environments	Equation	R^2	SEE (g)
E0	A_B=4.6623+1.8077L_W	0.9654	0.2314
E1	A_B=6.3842+1.2508L_W	0.9151	0.0901
E2	A_B=3.9716+1.7705L_W	0.9313	0.1700
E3	A_B=0.0198L_W^2+1.0825L_W+2.3608	0.9458	0.1578

R^2 is coefficient of determination; and SEE is standard error of estimate.

The slopes of equation were quantify responses of ratio of leaf weight to above-ground biomass to various light conditions. The ratio of leaf weight to above-ground biomass was greatest in E3 light environment, and lowest in open light environment, and the ratio in E2 light conditions was lesser than that in E1 which its canopy was thinnest.

Often, with decreasing light availability, plants allocate more biomass to the above-ground parts, especially leaves, to increase photosynthetic leaf area. But the variation in ratio of above-ground biomass to leaf weight is confounded to examine the responses of seedlings surface in different light environments. Thus by using the two-surface method to design crown are appropriate for shade tolerance.

Self-similarity to seedling crowns

The two-surface method assumes that the relationship between the foliage area and the Euclidean surface, or volume, of crowns is described by a power function. This assumption corresponds to a central concept of fractal geometry, self-similarity (Mandelbrot 1983).

Because the squared term of Equation (4) is insignificant and the relationship has no inflection points (Table 3, Fig.1~4), this fact is consistent with self-similarity of tree crowns. Thus, seedling crowns are self-similarity, and Equation (4) can be used to calculate fractal dimensions.

Table 3. Testing self-similarity of *Picea koraiensis* seedling crowns under variety of light environments

Light environments	a	b	c	SEE
E0	-1.59	3.05	-0.055	0.13
E1	2.13	0.40	-0.11	0.09
E2	-6.93	6.36	-1.08	0.15
E3	-3.58	4.06	-0.70	0.11

SEE = standard error of estimate

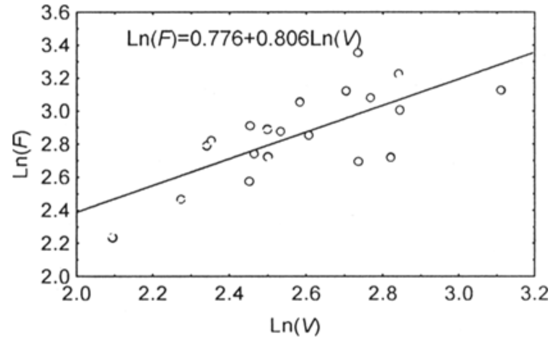

Fig 1. Relationship between Ln(*F*) and Ln(*V*) in open light environment (E0)

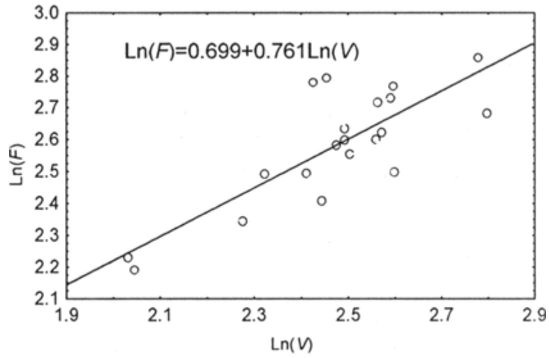

Fig 2. Relationship between Ln(*F*) and Ln(*V*) in E1 light environment

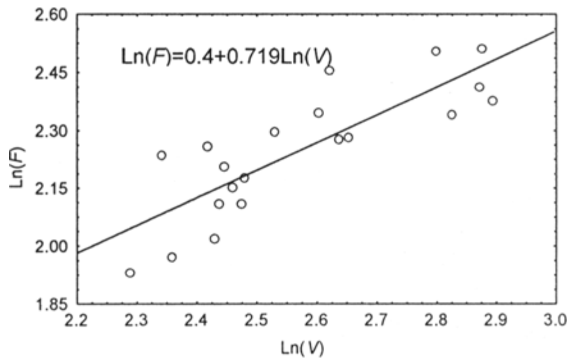

Fig 3. Relationship between Ln(*F*) and Ln(*V*) in E2 light environment

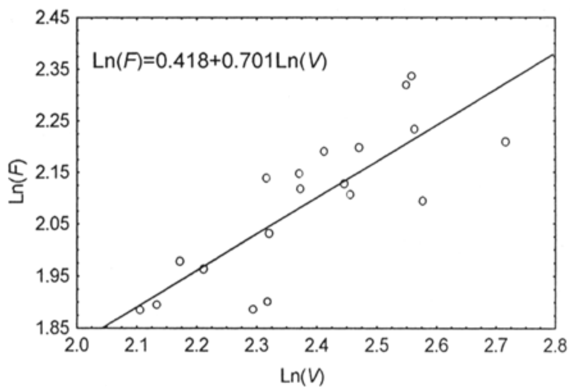

Fig 4 Relationship between Ln(*F*) and Ln(*V*) in E3 light environment

Fractal dimensions

Parameter D varied from 2.5728 to 2.1036, which showed that fractal dimensions of seedlings in open-light and low shade density is greater than in high shade density (Table 4). The results also show that moderate shading provides most advantages for the capturing limiting light resources through crown architecture.

Table 4. Fractal dimensions of *Picea Koraiensis* seedlings under variety of light environments

Light environments	Equation	R^2	D
E0	$\mathrm{Ln}(F)=0.7764+0.8062\mathrm{Ln}(V)$	0.69	2.4286
E1	$\mathrm{Ln}(F)=0.2640+0.8576\mathrm{Ln}(V)$	0.73	2.5728
E2	$\mathrm{Ln}(F)=0.4001+0.7189\mathrm{Ln}(V)$	0.73	2.1567
E3	$\mathrm{Ln}(F)=0.4181+0.7012\mathrm{Ln}(V)$	0.68	2.1036

A dimension of two would indicate that foliage does not tolerate shading and is located exclusively on the crown periphery so that its mass and surface are proportional to the surface of the hull. A value of three would be possible only if foliage was extremely tolerant to low light. Actual values are located between these extreme cases (Zeide 1991). In this study, it is not surprising that some correlation between fractal dimensions and species tolerance was detected. In addition to tolerance, crow structure could affect fractal dimensions. Deep penetrating cavities in the crown would let the sunlight in and would result in a substantial density of foliage inside the crown of even intolerant species. But high dimension of crown obtained in term of moderate shading, and fractal dimension was least in extreme low light conditions. Thus *Picea koraiensis* seedlings can be achieved most efficient tolerance to low light in term fractal dimension was maximum, and when fractal dimension was least, the efficiency of morphological capacity was extremely tolerant by lower light conditions.

Conclusions

With the change of light environment, crown characters of *Picea koraiensis* seedlings exhibited a greater plastic in lateral number, lateral increment, lateral dry weight, and specific leaf area. Changes of lateral can be more efficient in capturing in term of moderate shading. On a dry leaf mass, the increment rates of above-ground biomass was minimum in open light environment (E0) and it was maximum for seedlings grown in low light conditions (E3).

Although the range of calculated fractal dimensions of seedling crowns was confined between two and three, maximum of fractal dimension achieved in term moderate shading and in extreme low light conditions fractal dimension was least. The results shows that fractal dimension of crowns can be directly applied to quantifying surfaces, and can serve as an indicator shade tolerance of species.

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